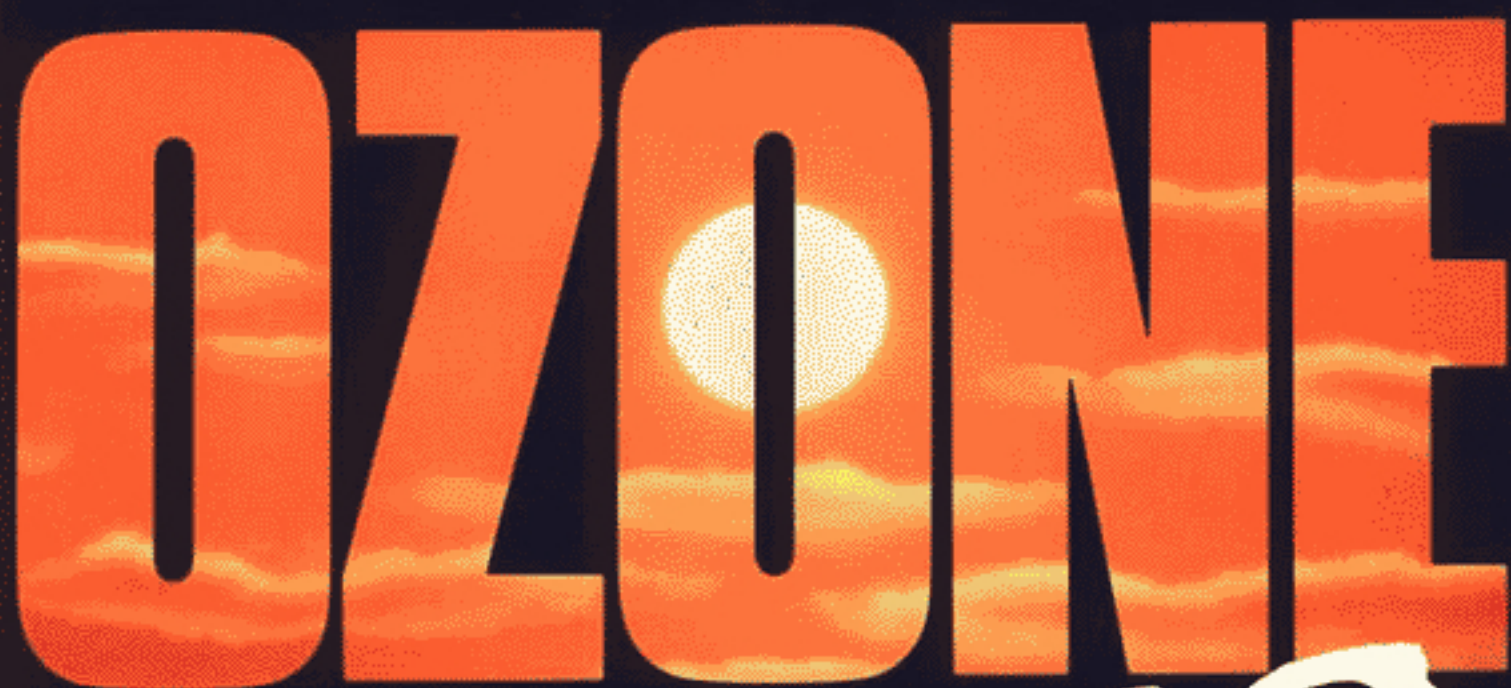


The 15 Year Evolution of a
Sudden Global Emergency

OZONE



CRISIS



SHARON L. ROAN

Foreword by Senator Al Gore

Timeline

December 1973: Rowland and Molina discover that CFCs can destroy the ozone in the stratosphere.

June 1974: Rowland and Molina's paper on their discovery is published in *Nature*.

September 1974: Rowland and Molina discuss their theory publicly for the first time at the American Chemical Society meeting in Atlantic City.

October 1974: A government committee recommends that the National Academy of Sciences conduct a study on the validity of the CFC-ozone theory.

December 1974: First government hearings are held on the CFC-ozone theory.

May 1975: The CFC-ozone theory is hotly debated at the American Chemical Society meeting in Philadelphia.

June 1975: The Natural Resources Defense Council sues the Consumer Product Safety Commission for a ban on CFCs used in aerosol spray cans.

June 1975: Johnson Wax, the nation's fifth largest manufacturer of aerosol sprays, announces it will stop using CFCs in its products.

June 1975: A government task force called IMOS defers the decision to regulate CFCs to the pending NAS report.

June 1975: Oregon becomes the first state to ban CFCs in aerosol sprays.

July 1975: The Consumer Product Safety Commission rejects the NRDC's lawsuit saying there is insufficient evidence that CFCs harm the ozone layer.

September 1976: The National Academy of Sciences releases its report verifying the Rowland-Molina hypothesis, but says government action on CFC regulations should be postponed.

October 1976: The Food and Drug Administration and Environmental Protection Agency propose a phase-out of CFCs used in aerosols.

March 1977: The United Nations Environmental Programme holds the first international meeting to discuss ozone depletion.

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- May 1977:** Several government agencies announce joint plans to limit the uses of CFCs in aerosols.
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- July 1977:** Harvard scientist Jim Anderson finds an abnormally high level of chlorine oxide in the atmosphere, throwing the CFC-ozone theory into question.
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- February 1978:** Government decides to postpone Phase Two regulations on CFCs used in refrigeration, air conditioning, solvents, and other industrial processes.
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- June 1978:** The original deadline for Phase Two regulations passes with no action taken.
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- October 1978:** CFCs used in aerosols are banned in the United States.
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- November 1979:** A second NAS report on the CFC-ozone theory is released, putting depletion estimates at 16.5 percent and saying a "wait-and-see" approach to regulations is not practical.
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- April 1980:** The EPA announces the United States' intention to freeze all CFC production at 1979 levels.
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- October 1980:** The EPA, under the Carter administration, releases an Advanced Notice of Proposed Rulemaking outlining plans for additional CFC regulations.
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- May 1981:** EPA director nominee Anne M. Burford testifies at her confirmation hearings that she views the CFC-ozone theory as highly controversial.
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- July 1981:** Hearings are held in Washington to discuss protection of small businesses from possible new CFC regulations. Hearings are highly critical of the Advanced Notice of Proposed Rulemaking.
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- August 1981:** NASA scientist Donald Heath announces that satellite records show ozone has declined 1 percent.
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- March 1982:** The NAS releases a third report on CFC-ozone and predicts eventual ozone depletion of 5 to 9 percent.
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- March 1983:** Burford resigns from EPA. Plans for additional CFC regulations are renewed under new EPA chief William Ruckelshaus.
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- April 1983:** During international talks, Norway, Sweden, and Finland submit a world plan for a worldwide ban of CFCs in aerosols and limitations on all uses of CFCs.

- February 1984:** A fourth NAS report downplays the potential harm to the ozone layer from CFCs by lowering depletion estimates to 2 to 4 percent.
- June 1984:** At a scientific meeting in Germany, Rowland reports his calculations on heterogeneous reactions involving hydrogen chloride and chlorine nitrate—reactions that could significantly speed up ozone depletion.
- November 1984:** The NRDC sues the EPA for failing to provide Phase Two regulations on CFCs as specified by the Clean Air Act.
- October 1984:** A British research group led by Joe Farman detects a 40 percent ozone loss over Antarctica during the austral spring.
- January 1985:** Lee Thomas takes over as EPA director.
- March 1985:** The Vienna Convention, calling for additional research and the exchange of information on ozone depletion, is signed by international negotiators. Negotiators fail to agree on worldwide CFC regulations.
- May 1985:** Farman's paper is published in *Nature*.
- August 1985:** NASA's Heath shows satellite photos confirming the existence of an ozone hole over Antarctica.
- January 1986:** A NASA-UNEP report warns that damage to the atmosphere is apparent.
- January 1986:** EPA releases its Stratospheric Ozone Protection Plan which calls for new studies to determine whether additional CFC regulations are needed.
- March 1986:** Atmospheric scientists meeting in Boulder discuss plans for an expedition to Antarctica to study ozone depletion there.
- June 1986:** Papers are published by two research groups indicating chemicals and polar stratospheric clouds are responsible for ozone loss over Antarctica.
- June 1986:** Hearings on ozone depletion and greenhouse warming are held in Washington. Thomas announces that some government intervention may be needed to halt emissions of gases that could harm the atmosphere. Scientists testify that greenhouse warming has begun due to emissions of gases such as CFCs.
- June 1986:** CFC manufacturers suggest that safe substitutes for the chemicals might be possible for a high enough price.

- August 1986:** Thirteen U.S. scientists depart for Antarctica on the National Ozone Expedition.
- September 1986:** A major CFC industry lobbying group announces it will support limits on CFC growth.
- September 1986:** The Du Pont Corporation announces it will call for limits on worldwide CFC production.
- October 1986:** During a press conference from Antarctic, U.S. scientists say they suspect chemicals are to blame for ozone losses there.
- November 1986:** Scientists favoring weather processes—or dynamical—explanations of the Antarctic ozone loss air their views in a special edition of *Geophysical Research Letters*.
- December 1986:** International negotiations on ozone protection resume in Geneva after a 17-month layoff. The United States proposes worldwide CFC reductions of 95 percent by the next decade.
- March 1987:** New evidence supporting a chemical explanation for the ozone depletion in Antarctica is revealed at a scientific meeting in Boulder.
- April 1987:** Under pressure from some high-level officials, the U.S. backs off on its original position and proposes long-term CFC reductions of 50 percent.
- May 1987:** Harvard scientist Jim Anderson completes a key instrument for confirming the chemical theories on ozone depletion in time for upcoming expedition to Antarctica.
- June 1987:** NASA's Heath reports satellite findings of a 4 percent ozone loss detected over a seven-year period. A NASA-sponsored study called the Ozone Trends Panel is organized to review the findings.
- July 1987:** The State Department announces a Personal Protection Plan as an alternative to CFC reductions. The plan is widely ridiculed.
- August 1987:** The McDonald Corporation, which uses CFCs in the making of polyurethane foam containers for hamburgers, announces it will stop using the chemicals.
- September 1987:** The Montreal Protocol is signed, calling for eventual worldwide CFC reductions of 50 percent.
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October 1987: The Antarctic ozone expedition ends with chlorine chemicals found to be the primary cause of ozone depletion.

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November 1987: A scientific conference confirms the findings of the Antarctic expedition.

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November 1987: U.S. lawmakers call for new negotiations to strengthen the Montreal Protocol.

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February 1988: Three U.S. senators ask Du Pont to stop making CFCs.

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March 1988: The chairman of Du Pont denies the request to stop making CFCs.

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March 1988: The U.S. ratifies the Montreal Protocol in a unanimous vote.

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March 1988: The Ozone Trends Panel announces it has found ozone losses of 1.7 to 3 percent over the Northern Hemisphere.

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March 1988: Three weeks after refusing to stop making CFCs, the Du Pont Corporation announces it will cease manufacture of the chemicals as substitutes become available.

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April 1988: Manufacturers of plastic foam food containers announce they will stop using CFCs.

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May 1988: Preliminary findings of a hole in the ozone layer over the Arctic are discussed at a scientific conference in Colorado.

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June 1988: A leading scientist says the greenhouse effect is impacting the earth and blames the use of manmade pollutants for the global warming.

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August 1988: The EPA orders domestic CFC reductions that mirror the terms of the Montreal Protocol.

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September 1988: The EPA says new evidence shows that it underestimated the degree of ozone depletion and says 85 percent cutbacks on CFCs are needed.

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October 1988: Scientists meeting in the Netherlands confirm the Ozone Trends Panel findings of ozone losses in the Northern Hemisphere.

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March 1989: European countries and the United States agree to faster CFC reductions but developing countries oppose the new timetable citing the costs of substitutes and scientific uncertainty.

Discovery

January 1973—December 1973

It was a few days before Christmas, and Mario Molina knew he would have a tough time locating his postdoctoral adviser, Sherry Rowland, if he didn't move fast.

Searching the dull green halls of the five-story Physical Sciences Building, Molina's mind raced. It was crazy, the young chemist told himself. The calculations didn't make sense. But he had checked them repeatedly, he assured himself. He had checked them a dozen times. What would Rowland say?

It was 1973 and Molina had only been at the University of California, Irvine, a small but rapidly growing campus 40 miles south of Los Angeles, for about five months. He had completed his Ph.D. for work on chemical lasers in the prestigious chemistry department at the University of California, Berkeley, and was proud of the accomplishment. Chemical lasers was an important field. But now, here he was, only months into his first salaried, faculty-research position, and he had volunteered to study a problem in atmospheric chemistry—something he knew practically nothing about. What if he were wrong about this? Molina spotted Rowland up ahead in the hall and picked up his pace. Then again, he drew in a deep breath, what if he were right?

Rowland looked harried. He was about to depart for a five-month sabbatical in Vienna. The holidays were nearing and he had much to do before he left. But Rowland was known for his patience and his ability to get things done under extreme pressure. He gave Molina his full attention.

"Hey, we better talk before you leave," Molina said. "I may have found something important."

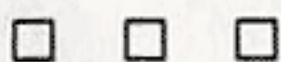
The two conferred for a few minutes and agreed to meet again later that afternoon. Within hours Rowland had cleared his busy schedule and settled into his cluttered corner office to go over Molina's calculations. While showing no outward emotion in front of Molina, Rowland was stunned. He, too, thought there must be an error. Where was it? Why couldn't the two of them find it? This was just too implausible.

The two men poured over the calculations for the next two days, not once discussing the implications of the work. And yet both of them knew that the equations they had scribbled could reveal a profound, almost unthinkably horrible secret about the earth's delicate atmosphere. If their work was correct, then a common class of manmade industrial chemicals called chlorofluorocarbons, or CFCs, signaled big trouble for the environment and, inevitably, the human race.

CFCs were widely used as aerosol spray propellants and refrigerants and, in 1973, were being produced worldwide at the rate of almost a million tons per year. People assumed that CFC emissions were harmless. But Rowland and Molina's calculations showed that the gases would eventually rise to the upper atmosphere and begin destroying ozone, the thin layer of gas that rests about 8 to 30 miles above the earth and shields it from the searing effects of the sun's ultraviolet light.

Imagine an eighth of an inch of snow dusting the entire world. The ozone layer is only as thick as that. This trace of ozone protects the earth. And yet its role is essential to the continuance of life. Now, Rowland and Molina suddenly realized, human activities could be destroying it and doing the job rather quickly. Rowland left his office that night and went home without the feeling of excitement that one would expect from a scientist who had toiled for years doing basic research and had now made a major discovery. Instead, he felt something of a burden.

"The work is going well," he told his wife, Joan. "But it looks like the end of the world."



"I got a chilly feeling," Rowland told a *Newsday* reporter shortly after the discovery became public. "Suddenly, something runs down your

spine. It's no longer the same thing; it's not the same circumstances as the usual experiment. You see potential danger for the environment of the world. My immediate reaction was disbelief. I thought I must have done something wrong."

A chemical reaction that could trigger a dramatic shift in the earth's superbly balanced climate was not what Rowland or Molina expected to find when they began looking at the chemicals in the fall of 1973.

The idea of studying CFCs had been nothing more than an interesting idea when it occurred to Rowland during a meeting sponsored by the Atomic Energy Commission in balmy Fort Lauderdale, Florida, almost two years earlier. As a radiochemist who had devoted his career to the study of how small molecules react and decay, Rowland had received funding for his research from the Atomic Energy Commission for years. The January 1972 meeting had been organized in order to bring together chemists and meteorologists—a gathering that seemed as odd as a bunch of pediatricians and gerontologists meeting to chat about the latest trends in medicine.

"There's a great difference in background," said Rowland of the two disciplines. "The typical chemist has had no courses in meteorology and the typical meteorologist has had maybe one course in chemistry."

It was not until the mid-1980s that one would expect a meteorologist to have had some training in chemistry. And the fact that, in 1972, meteorology and chemistry had not yet begun to merge may have been one reason no one had thought to look at what happened to manmade chemicals released in the upper atmosphere; the stratosphere was sort of a no man's land among atmospheric scientists. The thought certainly hadn't occurred to Rowland as yet, either, as he departed for Fort Lauderdale. Rowland had no background in atmospheric chemistry but was intrigued with the idea of applying his knowledge in radiochemistry to another field. He decided to attend the meeting to scout for some new ideas.

As was usual during scientific conferences, the coffee room chatter proved to be more interesting than some of the formal presentations. During one break between the talks and after a presentation on CFCs, Rowland heard an intriguing bit of news regarding work by the British scientist James Lovelock, a fiercely independent and creative chemist who had invented a much-heralded device, called an electron capture gas chromatograph, to detect atmospheric gases in minute amounts. Using his invention, Lovelock had, in 1970, discovered a

chlorofluorocarbon chemical called trichlorofluoromethane in the air over western Ireland—a surprising discovery since most pollutants rarely lingered for long in the atmosphere. Following up on that finding, Lovelock had discovered two commonly used CFCs—called CFC-11 and CFC-12 according to chemical industry shorthand—in the atmosphere at concentrations of 230 parts per trillion, which was equal to about one drop in a large swimming pool. Lovelock saw no reason to be alarmed by the apparent long, vigorous life of the chemicals in the atmosphere, however, noting that the highly stable CFCs might be useful to show how air masses moved. (Ironically, Lovelock's family was the first victim of the discovery that CFCs persist stubbornly in the air. Long before aerosol sprays containing CFCs were banned in the United States, the Lovelocks were forced to give up using aerosol sprays because they interfered with the measurements Lovelock was trying to make in his laboratory at home.)

The thing that struck Rowland as odd was that the concentrations of the gases Lovelock had measured appeared to be close to the total amount of CFCs being produced, suggesting the chemicals were drifting lazily up through the atmosphere with amazing endurance. The atmosphere, scientists knew, had a beautiful ability to cleanse itself of the earth's byproducts. Most chemicals were eventually washed out of the atmosphere through "sinks," removal processes in the lower atmosphere such as rain. But CFCs were apparently immune to these normal removal processes. Rowland returned to Irvine wondering what eventually became of the chemicals. But the question was not of pressing importance. He simply filed the matter away and didn't resurrect it for more than a year.

For the 46-year-old Rowland, having a stockpile of new problems to mull was crucial to his success as an academic chemist. If there was anything he feared in his career it was getting into a rut. And so far, he had successfully avoided that.

Born in Delaware, Ohio, Rowland was a fast learner who breezed through his studies at Ohio Wesleyan University where he majored in chemistry and minored in journalism. (The minor in journalism would later serve him well in his dealings with the press.) At 6 feet 5 inches, he wasn't too bad at either basketball or baseball and played both in college before moving on to complete his master's and doctoral degrees in chemistry from the University of Chicago. During graduate school, Rowland specialized in radiochemistry and had the good fortune of learning his discipline from Willard F. Libby, the Nobel-prize-winning scientist who invented carbon 14 dating. After four years at

Princeton University, Rowland accepted a faculty position at the University of Kansas and developed a reputation in radiochemistry, traveling throughout the world to attend scientific conferences in his specialty. By the time he agreed to head up the new chemistry department at the University of California, Irvine, in 1964, at the age of 36, he was relatively well known in his field.

"A well-known unknown," he called himself.

But in the summer of 1973, Rowland was anxious to study "something where the questions are a little bit different and the answers are a little more unknown." At UCI, he directed a small but eager group of young chemists. One of them, Mario Molina, showed particular promise and was also looking around for a research project.

The two men had met a few months earlier at a science conference, and Rowland was delighted when the young chemist chose Irvine to undertake his postdoctoral work in photochemistry. Molina was born in Mexico City, the son of an ambassador. Because of his obvious intelligence and his family's connections, Molina's career path was carefully laid out for him. He received some of his early education in Switzerland and earned a bachelor's degree in chemical engineering at the University of Mexico. After graduating, Molina spent almost a year in Germany at the University of Freiburg and later studied at the Sorbonne. The rather informal graduate-school programs in Europe were not to his liking, however, and Molina chose Berkeley to work on his Ph.D. in order to study under a highly respected chemist named George Pimentel. By the time he joined Rowland's research group in October of 1973, Molina was in his late twenties.

It was Rowland's practice to offer his postdoctoral students a choice of problems to study. One of the problems was tracing the whereabouts of CFCs in the atmosphere, and Rowland was pleased when Molina selected the topic and set off happily to try to come up with some answers.

"We thought it would be a nice, interesting, academic exercise," Molina said later. "We both knew that these CFCs were rather stable so there was nothing obvious that would damage them soon after they would be released. But that's about as much as I knew at the time."

Molina, a slightly built man with a calm demeanor and intense brown eyes, proceeded to tackle the problem in his usual studious and methodical manner. For several weeks, he spent much of his time in the campus library, reading books on atmospheric chemistry and proceeding to the more sophisticated scientific literature. Part of his

preparation was to look at how other compounds reacted in the atmosphere. Eventually, he narrowed his focus to CFCs.

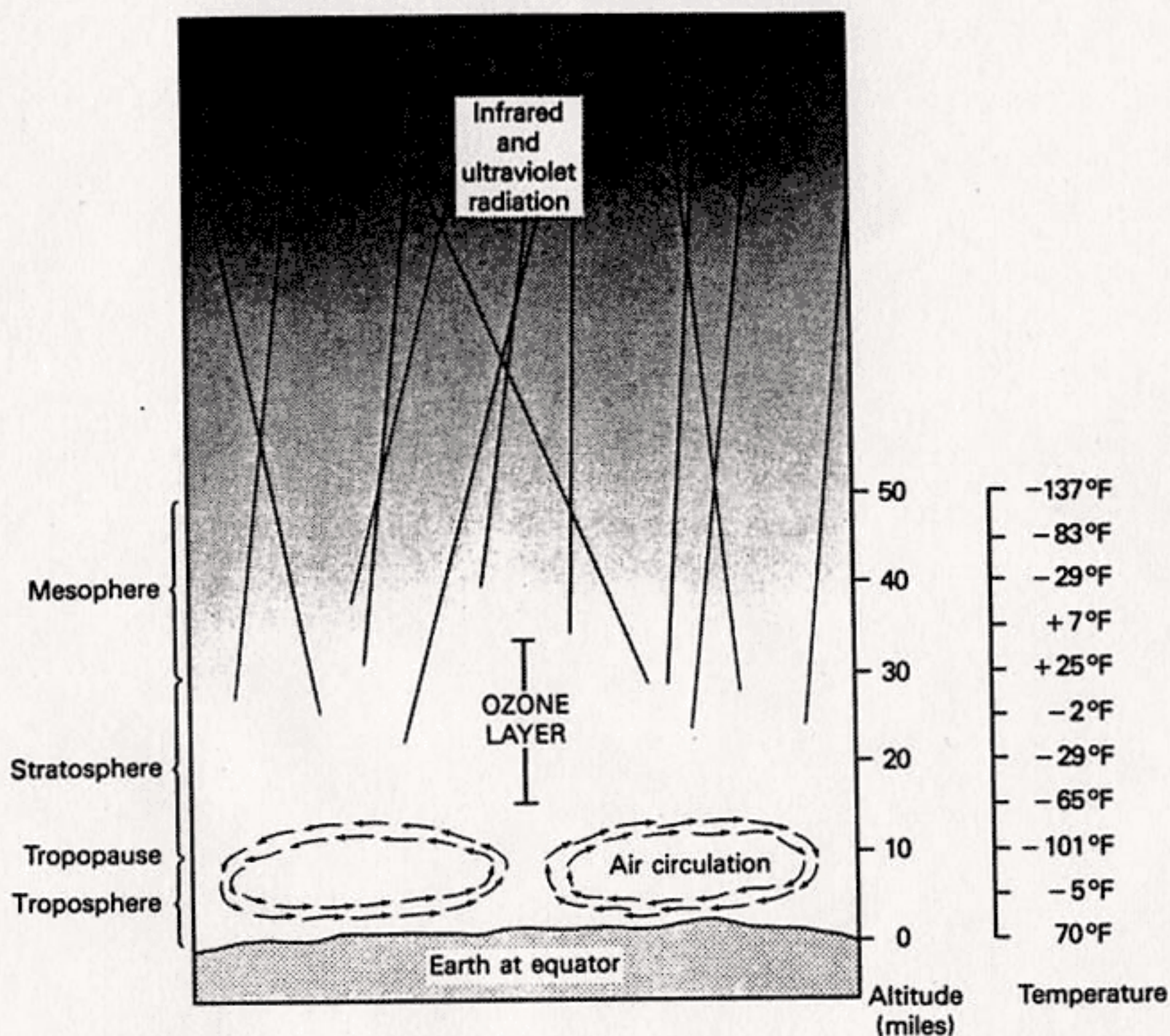
Molina knew that the total amount of CFCs in the troposphere—the part of the atmosphere between the earth's surface and about 6 to 10 miles in altitude where weather patterns formed—was about equal to the total amount produced. That was what Lovelock had found. So it appeared that the normal removal processes for gases reaching the troposphere didn't affect CFCs. Molina knew, for example, that rain would have to be ruled out as a disposal mechanism because CFCs were relatively insoluble in water. Finding no other removal processes for the chemicals in the troposphere, Rowland and Molina assumed that the chemicals were reaching the stratosphere, the next layer of the atmosphere, above the troposphere.



As far back as the Fort Lauderdale meeting it had occurred to Rowland that if CFCs reached the stratosphere they would be broken up by short-wavelength ultraviolet light. Since the chemicals do not absorb the longer wavelengths of sunlight they would not be attacked in the lower atmosphere. But, once they passed the protective ozone blanket, short-wavelength radiation would easily break them down into other compounds and atoms in a process called photodissociation. In particular, Rowland and Molina deduced that the photodissociation would allow for the release of free chlorine atoms from CFCs. They also estimated that the CFCs' journey to the stratosphere was a slow one. They calculated that it would take between 40 and 150 years for chemicals released on earth to reach their demise.

Satisfied, the two chemists concluded that there was no sink for CFCs other than the stratosphere and thought about writing up the results of the work for publication. But, Rowland told Molina, "We might as well be complete about it and find out what's going to happen to the chlorine."

Molina now had to consider how the chlorine would react with the thin, wafting layer of ozone in the stratosphere. Ozone is the product of sunlight acting on oxygen. While ordinary oxygen molecules have two atoms, ozone is made up of three oxygen atoms and is unstable, meaning that it is always willing to give up one of its oxygen atoms to other gases and turn back into oxygen. It is created when ultraviolet radiation or discharges of electricity split oxygen molecules



The earth's atmosphere is comprised of a series of layers at which different natural phenomena take place. The troposphere is the layer nearest the earth. The next layer, the stratosphere, is about 13 to 35 miles in altitude. Here, the ozone layer absorbs the sun's ultraviolet light and temperatures begin to rise with altitude. The next layer is the mesosphere where temperatures begin to fall again. The ionosphere marks the upper boundary of the atmosphere.

into single oxygen atoms. The oxygen atoms then link with oxygen molecules to form ozone. Derived from the Greek word *ozein*, meaning "to smell," ozone at ground level gives off a pungent, acrid odor that can sometimes be detected around leaking power lines, electric toy trains, or after a lightning storm.

Although it is no more substantial than a sheet of tissue paper wrapped around the earth, ozone protects life on earth. While ozone found at ground levels contributes to smog, the gauzy layer in the stratosphere has two purposes, and both of them are beneficial to living things. First, ozone absorbs much of the sun's harmful ultraviolet

light and is the only substance that does so. Second, by absorbing some of the sun's rays, ozone creates the stratosphere—a layer of the atmosphere in which temperatures rise with altitude thereby regulating worldwide circulation patterns and keeping "weather" confined to the troposphere. Without ozone, temperatures in the atmosphere would gradually decrease. While ozone is constantly produced by the action of sunlight on oxygen it is not a plentiful substance. If ozone were compressed to the pressure at the earth's surface, it would consist of a layer only one-eighth of an inch thick.

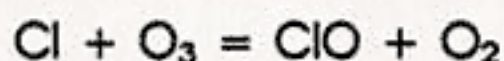
As Molina began working on the second half of his assignment, the fact that ozone was unstable raised some interesting questions about how it would react with other compounds in the stratosphere. But Molina could never have imagined what he was about to discover.

Using detailed calculations for chemical reactions, Molina concluded that each chlorine atom from CFCs would collide with a molecule of the highly unstable ozone. But the action didn't end there. Once the chlorine was freed from the chlorofluorocarbon, the by-product would be oxygen and a chemical fragment with an odd number of electrons called chlorine monoxide. Chlorine monoxide is a free radical, an unstable and highly reactive fragment with an odd number of electrons. The odd number of electrons in the fragment, Molina knew, guaranteed that it would react with a free oxygen atom in order to achieve an even number of electrons. Thus, he calculated, when the chlorine monoxide met the free oxygen atom, the oxygen in the chlorine monoxide would be attracted to the free oxygen atom and split off to form a new oxygen molecule. Chlorine would then be freed which would collide with ozone, thus starting the cycle all over again.

In short, the breakdown of CFCs by sunlight would set off a catalytic chain reaction in which one chlorine atom, like a monster Pac Man, could gobble up 100,000 molecules of ozone, turning them into impotent molecules of oxygen. Molina knew there were other catalytic reactions that occurred in the atmosphere—reactions in which one compound, the catalyst, could destroy another compound and would not be destroyed itself. But, if his calculations were correct, it looked as if the chlorine catalyst was an especially vigorous one.

Visions of environmental disaster hadn't yet marred Molina's thoughts, however. So the chemicals could take out a little ozone. What he really needed to know was just how much of the stuff was being dumped into the atmosphere so that he could estimate how much ozone might be lost. He knew other trace gases were released into

To be exposed to ultraviolet light, the CFCs must move upward, beyond the ozone layer. There, the UV light breaks the compounds down releasing chlorine atoms (Cl). The free chlorine atoms then attack ozone as follows:



effect: $\text{O} + \text{O}_3 = 2\text{O}_2$

In the first reaction, chlorine atoms destroy ozone to form chlorine monoxide (ClO) and normal oxygen (O₂).

In the second reaction, the Cl atom is regenerated and is free to start the cycle over again. The atom of oxygen that is lost in the second reaction is the equivalent of another ozone molecule lost because, otherwise, O and O₂ would have formed ozone (O₃).

The final effect is that two molecules of ozone are consumed each time the cycle is repeated. Chlorine is freed in each cycle to begin the process over again.

How chlorine destroys ozone.

the atmosphere all the time through natural mechanisms and that the biosphere continued to maintain its harmonious balance. It was unlikely, he figured, that a manmade chemical could outmuscle natural reactions in the atmosphere.

"I was thinking that (the effect) would be negligible because one normally thinks of natural processes on a global scale as being much larger," Molina said.

But nature was about to be outdone by the chemical industry. Checking industry figures for the amount of CFCs produced in 1972, Molina converted the figures into scientific units. He stared at his note pad and immediately suspected an error.

He rechecked the figures and, finding nothing amiss, began leafing through industry production figures to compare the amount of CFCs produced to another chemical, such as the nitrogen oxides—nitric oxide and nitrogen dioxide—which are produced in the atmosphere from nitrous oxide. Known as laughing gas, nitrous oxide was also used as an aerosol propellant. Molina saw that, compared to the production of nitrous oxide, CFC production was overwhelming.

He had to find Rowland fast.



Within a couple days, Rowland and Molina had reached a conclusion about the effects of CFCs in the atmosphere. They calculated that the amount of CFCs released that year—almost a million tons worldwide—would reach the stratosphere some 100 years later. Most of the CFCs released since the 1930s, when they were first manufactured, hadn't yet reached the mid-stratosphere where the reactions could take place. Significant production of the chemicals hadn't even begun until the 1960s. So actual damage to the ozone layer wasn't yet apparent. The concept was based on a principle called steady state—the condition of the atmosphere in about 100 years, when the amount of CFCs destroyed in the atmosphere by sunlight would be equal to the rate at which they were released into the atmosphere. In other words, the amount of ozone being destroyed would be equal to the amount being created.

The chemists determined that, at 1973 levels, between 7 and 13 percent of the ozone layer would be depleted within about 100 years—enough ozone depletion to seriously alter life on earth.

It was just a few days before Christmas and Rowland now faced a difficult decision. He and his wife Joan were scheduled to depart for Vienna just after New Year's, thanks to a Guggenheim Fellowship Rowland had earned. It seemed the perfect irony, that, with a problem of potential global importance sitting before him in Irvine, he was about to go off on a sabbatical to look for something novel to do. He had all he could cope with in the Irvine chemistry department.

Before making any hasty decisions, however, Rowland decided to share the CFC discovery with a few people whose opinions he trusted. One was Dieter Ehhalt, an atmospheric chemist from Germany who was working at the National Center for Atmospheric Research in Boulder, Colorado, at the time. Ehhalt had done some similar work collecting air samples from balloons in order to look at trace gases and had attended the meeting in Fort Lauderdale where CFCs were discussed. Rowland telephoned Ehhalt and told him that he was interested in getting some of his air samples. "What for?" Ehhalt inquired.

"We've been doing some calculations on chlorofluorocarbons and it looks very interesting. There are very large concentrations of it," Rowland told him.

Ehhalt was puzzled. "There isn't very much of it there now."

"We've gone to steady state," Rowland answered.

Ehhalt paused. "Beautiful," he answered.

Immediately, Ehhalt had understood the implications of Rowland and Molina's calculations.

The other phone call Rowland made that week was to Al Wolf, a radiochemist at the Brookhaven National Laboratory who later developed the radioactive chemicals that serve as the basis for PET scanners used to diagnose illnesses. Rowland, who had known him since the early 1950s, called Wolf, explained the research, and told Wolf that it looked like there was a major threat from chlorofluorocarbons. Wolf's reaction was probably the soundest piece of advice Rowland was going to hear for a long, long while.

"Well," said Wolf, matter of factly, "I can tell you Du Pont's not going to stop making them."



There was one more person that Rowland and Molina wanted to see before making their findings known to the world. During the week between Christmas and New Year's, the pair boarded a plane for San Francisco to visit Harold Johnston, a chemist at the University of California, Berkeley.

Johnston was a courteous, Southern gentleman who could be very tough and outspoken. He was, perhaps, the perfect person for Rowland to speak to about his CFC-ozone theory. An expert in atmospheric chemistry, Johnston had studied the growing smog problem in Los Angeles in the 1950s. He was the author of several books on the atmosphere and was extremely knowledgeable about ozone and chemical reactions in the stratosphere. He also knew a thing or two about the kind of "reactions" that could be set off by mixing industry matters with the environment and politics. In 1971, Johnston had suggested that gases called nitrogen oxides, released in the exhaust from high-flying supersonic jets, could cause ozone depletion through the same kind of catalytic reaction Rowland and Molina were now talking about—a theory that had generated intense disagreement and, in 1973, was still the prime topic of discussion in atmospheric chemistry. Due to his research, Johnston had suffered occasional personal attacks from SST proponents.

Because he wasn't an atmospheric chemist, Rowland was only

slightly familiar with the debates over the fate of the proposed fleet of the tilted, dropped-nose aircraft. Supersonic jets, or SSTs, could bridge any two points on the earth within 12 hours, and the idea that environmental consequences might squelch this wondrous new technological development led to the acrimonious debate. Rowland had invited Johnston to speak on the Irvine campus a couple of times and knew that the ozone-SST issue was controversial. He knew Johnston could bring him up to date with what was known about chemical reactions involving ozone.

Before the debate over nitric oxides from SSTs, no one had really given much thought to the ozone layer and its sustenance. In 1930, an English scientist named Sydney Chapman attempted to explain how ozone was formed and destroyed in the atmosphere. Called the "Chapman mechanism," the scientist suggested that ordinary oxygen molecules (O_2) would absorb very short-wavelength ultraviolet light. Oxygen molecules make up 21 percent by volume of all atmospheric molecules while nitrogen takes up the bulk at 78 percent. Sunlight, Chapman said, would split apart oxygen molecules into two oxygen atoms (O). Atoms of oxygen would then attach themselves to other oxygen molecules to form ozone (O_3). Chapman also proposed that oxygen atoms could break up ozone molecules by colliding with them to produce two oxygen molecules. So, the Oxford scientist concluded, the rate of ozone being produced was equal to the amount being destroyed at any one time.

Until the SST debates and the studies they generated, few people were interested in processes that took place in the mysterious stratosphere. Meteorologists, for example, were usually more concerned with weather, which took place in the troposphere. People who launched rockets were more concerned with processes in the mesosphere—the layer of the atmosphere above the stratosphere. But, from the 1950s to the 1970s, a small enclave of scientists who met occasionally to discuss ozone studies concluded that the Chapman mechanism was not complete.

In the late 1950s, rocket measurements showed that the amount of ozone present in the stratosphere was much less than what theory suggested. By 1961, ozone researchers suspected that something else must be destroying ozone. In 1964, a Canadian researcher named John Hampson proposed that oxides of hydrogen, which were free radicals given off from water vapor, could be created in the stratosphere and could react with ozone in a catalytic reaction; the ozone was destroyed in the reaction but the catalyst, the oxides of hydrogen, was not. A few

years later, Australian scientist B.G. Hunt set up a computer model showing how oxides of hydrogen might account for the apparent ozone loss.

In 1969, however, the brilliant meteorologist of the University of Stockholm, Paul Crutzen, began to study the idea that activities on earth could affect the atmosphere. While on a sabbatical at Oxford, Crutzen, who had studied chemistry, wrote a paper that received very little attention suggesting that the oxides of hydrogen reaction was not important. In a second paper, a year later, Crutzen suggested that nitrous oxides, which could be emitted from natural sources such as solar flares, might be responsible for some ozone loss. Crutzen suggested that nitrous oxides, because of their inertness, would rise slowly to the stratosphere where ultraviolet radiation would convert the nitrous oxide to nitric oxide, a simpler form of the chemical. The nitric oxide would then initiate a catalytic reaction that could destroy ozone while leaving the nitric oxide molecules free to begin the chain reaction over again.

Crutzen's theory was interesting to some people but didn't generate much excitement. The source of nitrogen was small, too small to do any great harm to the ozone layer. But the work was to become more than just a nice bit of academic research. In 1971, congressional committees began to hear scientific arguments on the potential problems of SSTs (which released oxides of nitrogen) and to consider a bill to provide funding for the construction of two supersonic jet prototypes by the Boeing Company.

The SSTs were generating a lot of controversy. A study authorized by the Department of Commerce had found the jets posed no threat to ozone. But critics charged that the aircraft would be noisy and costly. And there was another potential problem. An atmospheric scientist at the University of Arizona, James McDonald, was suggesting that water vapor from the jets' exhaust could harm the ozone layer, allowing more ultraviolet light to reach the earth and causing an increase in skin cancers. Besides being one of the first scientists to suspect that manmade pollutants could disrupt the ozone layer, McDonald was perceptive enough to link the increased ultraviolet light from ozone depletion to an increase in skin cancers. However, the outspoken scientist suffered for his independent thinking. The link between skin cancer and the sun's radiation was not widely known in the early 1970s. And the suggestion didn't impress lawmakers when McDonald testified at congressional hearings on the SSTs in March of 1971.

Unfortunately, McDonald was an easy target for ridicule. A be-

liever in UFOs, he had once suggested that alien visitors might be responsible for power blackouts on earth. But, in the spring of 1971, he only wanted to warn Congress of his theory that water vapor from the exhaust of SSTs could destroy the ozone layer. Committee members grilled McDonald mercilessly, however. In their book *The Ozone War*, authors Lydia Dotto, a Canadian science writer, and Harold Schiff, a chemist, said committee members questioning McDonald seemed more concerned with his views on UFOs.

"It is not entirely clear that there is a relationship between SSTs and UFOs," McDonald protested to the committee, straining to be patient.

McDonald's theory was sound enough to cause considerable alarm among environmental groups and government officials, however. In March 1971, the Department of Commerce organized a scientific conference to study the impact of the SSTs on the atmosphere. Hal Johnston was invited to attend the meeting.

Johnston knew little about the SSTs at that point and listened with only mild interest as the theory of water vapor was discussed during the two-day meeting. McDonald's water vapor theory was soundly refuted during the meeting and was later completely disproven. But when someone raised the issue of whether oxides of nitrogen, also released in the jets' exhaust, might have some potential effect on ozone, Johnston perked up. He had earned his Ph.D. on a study of oxides of nitrogen and was familiar with the compound. Conference participants quickly dismissed the idea that oxides of nitrogen could be important in the atmosphere but Johnston knew better. He spoke up quickly, disagreeing with the consensus. But, he recalled later, "Nobody wanted to hear that at that meeting. There was quite an uproar over it."

Johnston returned to Berkeley incensed that the oxides of nitrogen mechanism was being ignored and went to work on a paper describing how the compound, released in the exhaust of supersonic jets, could cause a catalytic reaction in the stratosphere which would destroy ozone. He deduced that 500 SSTs flying seven hours a day would deplete ozone by at least 10 percent in one year's time. The paper was accepted by the respected journal *Science* and was published in August 1971. But by then it was old news. In a scandalous mixture of science and politics, someone (the culprit was never found) leaked a version of Johnston's paper to a small Bay Area newspaper in May, only days before a crucial Senate vote on whether to fund the

SSTs. With Johnston's findings out in the open, it was not surprising that the Senate defeated the SST measure.

Johnston's paper in *Science* was followed by a paper from Crutzen, also suggesting that oxides of nitrogen could have a major impact on the atmosphere. Concerned with the recent flurry of discoveries on the environmental impact of high-tech aircraft, the federal government ordered a multimillion-dollar study from the Department of Transportation to assess the threat of supersonic aircraft being developed by other nations. The Climatic Impact Assessment Program (CIAP) became the first intensive study of the effects of human activities on the atmosphere.

Ironically, research later showed that nitric oxides from supersonic jets were far less of a threat to ozone than had been previously suggested. The jets would fly too low to cause much damage. (Today, most scientists believe that a large fleet of high-altitude aircraft could cause substantial ozone depletion, however such a fleet has not been built. And there is controversy over the Department of Commerce's current position that the proposed "Orient Express" would not cause losses of ozone.)

Water vapor from the exhaust was never proposed as a possible threat to ozone again. Although no one would ever know if the grilling he took earlier that year contributed to his depression, James McDonald was found dead by suicide in mid-1971.



Studies for the Climatic Impact Assessment Program were well underway by the time Rowland contacted Johnston in December 1973. Johnston, a respected chemist, listened to Rowland's explanation of the CFC problem over the phone and, to Rowland, seemed interested although noncommittal. He would have to see more details of the work and review it. In his office, Johnston hung up the phone while experiencing the same conflicting emotions that Rowland and Molina had felt a few days earlier.

"That's terrific. That's terrible," Johnston muttered, impressed with the theory and yet horrified by its implications. But, he said later, "You could see immediately that it was very important."

Within days the Irvine scientists met in Johnston's Berkeley office and waited while Johnston reviewed the data carefully. He could find no errors in the work. In fact, Johnston informed Rowland and Molina

that they weren't the first to look at the reaction of free chlorine in the stratosphere.

Only a few months earlier, while Rowland and Molina were just beginning their work on CFCs, a CIAP meeting had been held in Kyoto, Japan. Attending the meeting was a young University of Michigan researcher named Richard Stolarski who was presenting a study completed by he and another Michigan scientist, Ralph Cicerone. Neither was an atmospheric chemist. Stolarski was a physicist and Cicerone had trained in electrical engineering with a minor in physics, but they were eager to study stratospheric problems and had begun a study under contract for NASA's Marshall Space Flight Center to determine the environmental effects of the proposed space shuttle. In particular, the pair decided to look at the hydrogen chloride emissions from the solid-fuel rockets.

Stolarski and Cicerone were young, inquisitive, and very sports-minded, often lugging their golf clubs to science conferences in the hopes of squeezing in a round after the meetings. Stolarski and Cicerone had been attending the CIAP meetings, had heard about the SST controversy with nitric oxide, listened to the wrangling over stratospheric chemistry, and thought the whole field was rather interesting. They wanted to get involved. And no one had thought about chlorine chemistry before.

"Chlorine chemistry was a neat way to get involved in it because it exhibited all the same kinds of things that the nitrogen oxide chemistry did but nobody cared about it," Stolarski later recalled. "So we thought we could very quietly work on it and not get involved in the incredible brouhaha that was going on then about SSTs. And if you were new in the field and weren't quite as sure of yourself, you didn't like to expose yourself until you learned a little better. It was a nice, quiet way to learn. But it didn't stay quiet very long. It just blew up in our faces. But it got us in the field."

In 1973, Stolarski and Cicerone had determined that the chlorine released from exhaust from the shuttle might deplete ozone. Initially, NASA officials seemed unconcerned with the findings. "Of course, chlorine will catalyze ozone destruction," the researchers were told by a NASA official. They were reminded that in the 1930s researchers had combined chlorine and ozone in the laboratory and had subjected it to light and had observed the ozone decrease. It was a known fact. In addition, the Michigan scientists' calculations showed the amount of ozone depletion that could be expected from the shuttle exhaust was a tenth of a percent.

It didn't seem to be a major problem. But NASA officials had to think about chlorine in combination with other environmental effects from the shuttle. And when Stolarski and Cicerone informed NASA of their findings and discussed publishing the work, some NASA officials said they preferred to keep the shuttle research quiet.

"There were all kinds of opinions within NASA as to what stand to take on something like this," Stolarski recalled. "There were certainly people early on trying to convince us that perhaps we didn't want to publish some of the things we found."

NASA, however, remained supportive of the research, Stolarski remembered. "Although the guys that supported us were, at times, a bit reluctant to advertise it."

Trying to be complete about their studies on chlorine in the stratosphere—and perhaps confused that they had touched a political nerve—Stolarski decided not to mention the effects of ozone depletion from the shuttle at the CIAP meeting in Kyoto. Instead, he suggested that chlorine, produced from natural sources such as volcanoes, could create a catalytic reaction to destroy ozone. The finding was of some interest, but not because anyone was worried about a sudden rash of volcanic eruptions.

Cicerone and Stolarski later spelled out the full consequences of chlorine from the space shuttle exhaust in a paper they submitted to *Science* magazine. After a long wait, the *Science* paper was rejected, having received a rather mixed and mediocre review. Cicerone immediately suspected some competitors had done the paper in, aghast over one comment made in the review of the paper which said, "This work is of no possible geophysical significance."

A special edition of the *Canadian Journal of Chemistry* was about to be published summarizing the proceedings at the Kyoto meeting, however. And although Stolarski and Cicerone were depressed about the rejection of their paper by *Science*, they were persuaded to submit it to the Canadian journal. The study appeared along with one by two Harvard researchers, Michael McElroy and Steven Wofsy, who had reached similar conclusions about chlorine from the shuttle after hearing Stolarski discuss the problem in Kyoto. Along with Rowland and Molina, Stolarski, Cicerone, McElroy, and Wofsy were all to become key participants in ozone-depletion arguments throughout the 1970s and 1980s.

The secret about the effects of the space shuttle's exhaust was out. But, Cicerone and Stolarski concluded, the spaceship was still on the drawing board and probably wouldn't release enough hydrogen

chloride to do much harm. Johnston suggested another version of NASA's reaction to the chlorine studies: "The people running the space shuttle program were trembling in their boots for a year or two to keep that from coming under the same kind of politics the SST ran in to," he said with characteristic candor.

The chlorine issue was dropped. Other than volcanic emissions and exhaust produced by the space shuttle, which wasn't even built yet, there was no other known source of free chlorine in the stratosphere.

But, six months later, Stolarski, a self-effacing person who is now known as a top researcher in the field, was kicking himself for limiting his thoughts to those two known sources of chlorine. There had been several hints about additional chlorine sources in the early 1970s that the two Michigan researchers had ignored.

In November 1973, Stolarski had attended a meeting in Houston where he encountered Charles Kolb, a scientist from Aerodyne in Cambridge, Massachusetts. Kolb had heard about the chlorine discussions at the Kyoto meeting and now pulled Stolarski aside in Houston.

"Have you thought about the Freons?" he asked Stolarski. "They are incredibly stable molecules and they've got to be a good source."

Stolarski, who was not a chemist, had no idea what a Freon was.

"Well, no, I hadn't really thought about it," he stammered, shrugging off the suggestion.

There was a second hint that also fell by the wayside. Stolarski had been discussing the chlorine research on occasion with Jim Walker, a Yale scientist. In November, Walker sent Stolarski a one-page Xerox of Lovelock's carbon tetrachloride measurements.

"Have you thought about carbon tetrachloride?" Walker had scribbled across the top. Stolarski and Cicerone hadn't and let the matter drop.

There was just too much work to do to look into every little suggestion. But Stolarski had no doubt that the chlorine research was important.

"Why are you studying the chlorine from the space shuttle?" a colleague asked Stolarski that winter. "It's such a trivial effect. You're calculating a tenth of a percent. Who cares?"

Stolarski's response was one of the few times, he recalled, that he has been on the money.

"We study it because it's interesting," he answered. "And some

day, somebody is going to invent a much bigger source that's going to be important."

Of course, somebody had long ago invented that much bigger source. And, unknown to Cicerone, Stolarski, Wofsy, McElroy, and others, two somebodies had just found it.



Johnston peered at Rowland and Molina in his Berkeley office and informed them that they had just found the first major source of free chlorine that warranted serious concern.

Having participated in the SST-ozone controversy, he knew the Rowland-Molina theory would stir up as much debate and inevitable rancor as the SST thing. He advised Rowland and Molina to begin making their case. The Irvine scientists obviously felt a deep moral conviction that they should speak out firmly and immediately about the potential dangers of CFCs. Because Johnston was familiar with such matters, Rowland and Molina inquired whether he would care to join them in raising the red flag on CFCs.

"No," Johnston told them, with a grin. "That's up to you." But before Rowland and Molina caught an evening flight back to Orange County, Johnston left them with some words to mull over.

"Are you ready for the heat?" he asked.